ION BEAM PROPERTIES AND THEIR DIAGNOSTICS FOR ECR ION SOURCE INJECTOR SYSTEMS

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Abstract

Electron Cyclotron Resonance (ECR) ion sources are essential components of heavy-ion accelerators due to their ability to produce the wide range of ions required by these facilities. The ever-increasing intensity demands have led to remarkable performance improvements of ECR injector systems mainly due to advances in magnet technology as well as an improved understanding of the ECR ion source plasma physics. At the same time, enhanced diagnostics and simulation capabilities have improved the understanding of the injector beam transport properties. However, the initial ion beam distribution at the extraction aperture is still a subject of research. Due to the magnetic confinement necessary to sustain the ECR plasma, the ion density distribution across the extraction aperture is inhomogeneous and charge state dependent. In addition, the ion beam is extracted from a region of high axial magnetic field, which adds a rotational component to the beam, which leads to emittance growth. This paper will focus on the beam properties of ions extracted from ECR ion sources and diagnostics efforts at LBNL to develop a consistent modeling tool for the design of an optimized beam transport system for ECR ion sources.

INTRODUCTION

Because of their versatility, reliability, and their ability to produce ions throughout the periodic system ECR ion sources have become the injector of choice for many heavy ion facilities. Furthermore, the development and refinement of ECR ion sources over the last three decades has provided remarkable improvements in their performances. For example in 1974, the first ECR ion source Supermafios produced 15 eμA of O^{6+}, 30 years later in 2003 the VENUS (Versatile ECR ion source for Nuclear science) ECR ion source produced 2.8 emA of O^{6+}. These remarkable improvements were made possible by advances in permanent magnet strengths, and ECR design technology. The main driving components for improving the performance of ECR ion sources were formulated in Geller's famous ECR scaling laws, stating that higher magnetic fields and higher frequencies will increase the performance of ECR ion sources. Following these scaling laws a series of ECR ion sources were developed using normal conducting magnet technology and permanent magnets. In the last decade with advances in superconducting magnet technology, the next generation of high field superconducting sources has been developed utilizing frequencies of 24 to 28 GHz and magnetic confinement fields of several Tesla. These third generation superconducting ECR sources are now the injector of choice for next generation heavy ion facilities such as the Radioactive Ion Beams Factory (RIBF) at RIKEN, and the Facility for Rare Isotopes (FRIB) proposed to be built at Michigan State.

The magnetic fields in an ECR ion source serve both to confine the plasma and to provide a closed surface where the microwave can heat the electrons through electron cyclotron resonance. In most ECR ion sources the magnetic confinement fields are produced by combining a radial sextupole field with an axial mirror field, which provides a magnetic field increasing in both radial and axial directions. This "minimum-B" field configuration produces stable and dense plasmas. The magnetic field strength must be optimized for the selected ECR heating frequency to ensure efficient electron heating in addition to strong confinement. Ideally, the radial field strength should be twice the resonant field. The axial solenoid-mirror field-strength on the injection side of the ion source can be three to four times the ECR resonant field, while it is typically 2 times the resonant field at the extraction end. In case of the VENUS ECR ion source, which has been developed as prototype injector for Facility for Rare Isotopes FRIB and was designed for optimum operation at 28 GHz, the corresponding electron cyclotron resonance field strength is 1 T, but in order to achieve sufficient plasma confinement, the magnetic field at in injection are in the between of 3.5 to 4 T, at extraction 2 to 2.5 T and 2T radially at the plasma wall.

HEAVY ION INJECTOR BEAMS

In the last 10 years, the intensity and charge state requirements for the next generation nuclear science facilities have increased dramatically. For example for FRIB and RIBF, the intensities required for the heaviest ion beams are more than an order of magnitude higher than routinely used at currently operated heavy ion facilities. In particular, uranium beams are one of the most important and challenging beams for these facilities and will be used as an example to describe the characteristics of ion beams produced by ECR ion sources. For both facilities, about 0.5 mA uranium ion current is required from the front end of the driver LINAC (in the case of RIBF as a single charge beam of U^{35+} and in case of FRIB as combined current of U^{33+} and U^{34+}).

Of all currently operating ECR ion sources the fully superconducting ECR ion source VENUS at LBNL has produced the highest uranium intensities to date:

namely about 0.2 mA of uranium in the charge states 33+ to 35+, which is close to the requirements of FRIB, but about a factor 2 lower than required by RIBF in RIKEN. As illustration, figure 1 shows a charge state distribution (CSD) of such a high intensity uranium spectrum from the VENUS source. The following general characteristics for ion beams extracted from ECR ion sources can be noticed in figure 1. Besides the charge state required by the accelerator many more charge states are present in the extracted beam (in case of uranium 20 or more). In addition, the beam also contains high intensity oxygen ion beams, since oxygen gas is routinely used in ECR ion source plasmas to enhance the heavy ion charge state performance. Consequently, several milliamps of total heavy-ion-beam current have to be extracted and transported. Space charge in the extraction region and the beam line become important challenges for the design of the analyzing system and beam line. In addition, the beams have to be extracted from a high magnetic field region at the peak of the source solenoid field at the extraction, which influences the beam depending on the magnetic rigidity of the ions.

As the uranium example shows, even today's highest performance ECR ion sources cannot or can only barely match the intensity requirements of the next generation heavy ion accelerators for the heaviest beams. Therefore, a better understanding and careful optimization of the ion beam transport system has become a necessity and a focus of the ECR ion source community. Ion beam diagnostic systems have been developed to measure the properties of the extracted and transported ion beams.

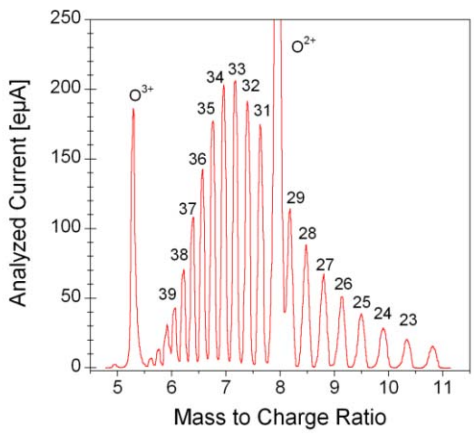

Figure 1: Uranium charge state distribution for a high intensity tune optimized for 33+ to 34+.

The multispecies ion beams make ECR ion source injectors and front ends inherently more complicated than single species injectors. In addition, the user programs at heavy ion facilities typically require a wide variety of ion species, e.g. in cases of FRIB more than 40 ion species (many of which are rare and expensive isotopes). For the different driver beams the ion beam intensities required by the driver LINAC vary widely in order to maximize the available beam power on target. Therefore the front end cannot be optimized on a single ion beam or intensity.

In the following sections, ion beam diagnostic methods for ion beams extracted from ECR ion sources are discussed. Data are presented for the VENUS ECR ion source which was characterized for a wide range of ion beams to obtain data for the FRIB LINAC driver design.

ION BEAM EMITTANCE DIAGNOSTICS

As in most other injector ion beam lines, emittance scanners are an important part of the ion beam diagnostics. All the typical methods such as electrostatic scanners (Allison-type), slit scanners, wire scanners, as well as pepperpot scanners are in use [1]. Since these diagnostic methods are well established and described in detail elsewhere, the principles are summarized only briefly below.

For the Allison-type emittance scanner [2], the beam enters through an entrance slit, gets deflected by parallel plates through the exit slits where the signal is detected in a Faraday Cup. The Faraday Cup signal is measured in dependence of the deflection voltage. The divergence of the beam is calculated from the applied voltage on the deflection plate and the length of the applied electric field (see Figure 2)

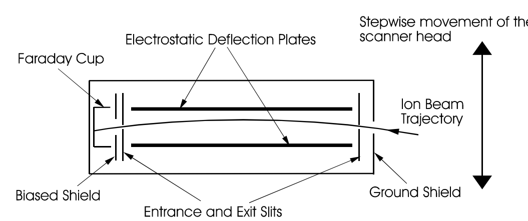

Figure 2: Measurement principle of the electrostatic emittance scanner.

The beam divergence is determined for each location as the scanner is moved stepwise through the beam. By scanning the beam with a second unit (rotated by 90 degree), the ion beam emittance in both transverse directions (x and y) can be measured. The resolution of this method is only limited by the width of the entrance and exit slits and the lengths of the deflection plates and can provide high resolution emittance data. However, the disadvantages of this type of emittance measurement method are that the scans are rather slow and that the ion beam intensity is integrated over the slit opening of the scanner (the same is true for wire and slit scanners).A pepperpot emittance scanner on the other hand can give fast, time-resolved 4D emittances. In this case a hole mask is inserted into the beam and the beam is imaged on a scintillator downstream. Figure 3 shows an example of a pepperpot diagnostics instrument developed at the KVI in Groningen [3].

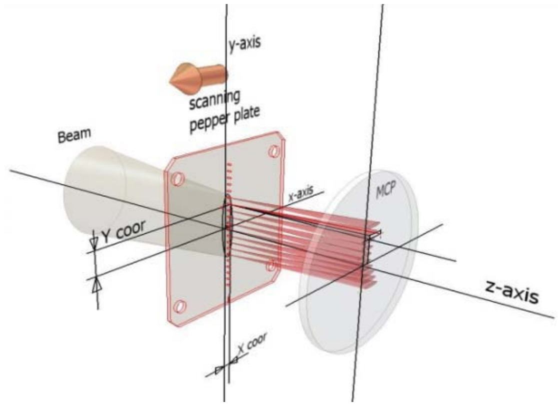

Figure 3: Pepperpot emittance scanner developed at KVI, Groningen. Image taken from [3].

As the scanner collects both transverse angles and locations simultaneously, two dimensional data can be extracted. This opens the possibility to extract coupled phase space information and to diagnose fast transient effects in the plasma. For this reason, scintillator based as well as multichannel plate pepperpot scanners are being developed in many ECR ion source groups [3-5].

ION BEAM EMITTANCES FOR BEAMS EXTRACTED FROM ECR ION SOURCES

As described in the previous section, the ion beam properties of ions extracted from ECR ion sources are complex. Therefore, their characteristics are discussed in detail in the next section and put into context with experimental measurements performed on the VENUS ECR ion source.

For an ECR extraction system two main contributions to the ion beam emittance have to be considered [6] the ion beam temperature and the induced beam rotation due to the decreasing axial magnetic field present at the extraction aperture.

The emittance due to the ion temperature can be estimated by assuming a Maxwellian temperature distribution inside the plasma:

$$\varepsilon_{TEMP}^{xx'-rms-norm} = 0.016\, r \sqrt{\frac{kT_i}{M/Q}} \qquad (1)$$

where ε is the normalized x-x' rms emittance in π mm mrad, r is the plasma outlet hole radius in mm, kT_i is the ion temperature in eV, and M/Q is the ratio of ion mass in amu to ion charge state and is dimensionless.

Assuming an uniform plasma density distribution across the plasma outlet hole, the emittance due to beam rotation induced by the decreasing magnetic field in the vicinity of the extractor can be described by Busch's theorem (assuming $\varepsilon^{100\%} = 5 \cdot \varepsilon^{rms}$, a waterbag distribution):

$$\varepsilon_{MAG}^{xx'-rms-norm} = 0.032 \cdot r^2 \cdot B_0 \cdot \frac{1}{M/Q} \qquad (2)$$

where ε is the normalized x-x' rms emittance in π mm mrad; r the plasma outlet hole radius in mm; B_0 the axial magnetic field [T]; M/Q is the ratio of ion mass in amu to ion charge state and is dimensionless.

The beam rotation due to the decreasing magnetic ECR ion source field becomes the dominating contribution to the ion beam emittance when following condition, as derived by combining equation (1) and (2), is satisfied:

$$B_0 \cdot r \geq 0.5 \cdot \sqrt{kT_i} \cdot \sqrt{M/Q} \qquad (3)$$

Following the estimate by M. Leitner et. al [6], Table 1 summarizes the minimum magnetic field values where the emittance value starts to be dominated by the ion beam rotation. In the table, the VENUS plasma outlet aperture radius of 4 mm and an assumed ion temperature of 2 eV is used to compute the maximum field values. Keeping in mind that the extraction field of third generation superconducting ECR ion sources is in the order of 2 T, it is evident that the magnetic field is the main contributor to the ion beam emittance for these high field sources. However, the same is true for most ECR ion source operating above 6 GHz.

Table 1: Magnetic field values where the emittance starts to be dominated by the ion beam rotation for light to heavy ions

Ion	M/Q	Magnetic field at extraction
H^+	1.00	>0.18 T
O^{6+}	2.67	>0.29 T
Ar^{8+}	5.00	>0.40 T
Xe^{18+}	6.89	>0.46 T
U^{33+}	7.21	>0.47 T

An important consequence of this dependence is that the emittance values of the ions extracted from ECR ion sources are dependent on the magnetic rigidity. Therefore, once the magnetic field at the extraction region is defined for the ECR injector, a rough estimate of the emittance can be made using equation (2).

As an illustration, Figure 4 shows the calculated magnetic emittance for FRIB ions over the operation region for 1 T and 2 T fields (heating frequency range from 14 GHz – 28 GHz) and 8 mm diameter extraction aperture. Because the ion beam emittances are strongly dependent on the beam rigidity the acceptance of the accelerator (which is constant for all ions) has to be chosen carefully to match the ion beam over the required range or emittance defining collimators must be used to define the beam emittance in the low energy beam transport (LEBT).

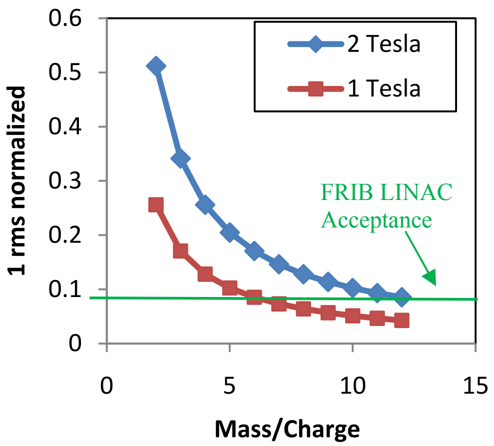

Figure 4: Calculated 1 rms normalized magnetic emittance for FRIB driver linac ions for 1T and 2 T fields at extraction. The FRIB driver linac acceptance of .1 π mm mrad is also indicated.

From figure 4, one might expect that it would be best to choose low frequencies, low magnetic field ECR ion sources as injector to minimize the emittance. This is true for low and single charge state ions, but for high charge state ions the increase in density in higher performance sources exceeds the emittance increase due to the increase in magnetic field. In addition, experiments [7] have shown that the simple model described in the previous section is not sufficient to explain the measured emittance values and that the ion confinement in the plasma plays an important role for the extracted ion beam emittance.

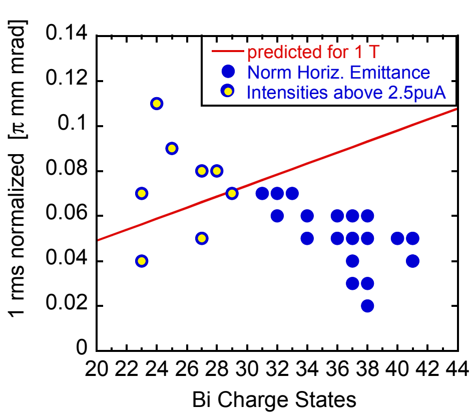

Figure 5: Emittance value versus ion charge state for bismuth extracted from a 1T axial field. As comparison, the predicted emittance dependence from the magnetic field is also shown.

Measurements indicate that within an ion charge state distribution, higher charge state ions have lower emittances than lower charge state ions, a trend which contradicts the theoretical prediction. As an example, figure 5 shows an emittance measurement for medium to high charge state ions of Bi extracted from the VENUS ECR ion source with a 1 T magnetic field present at the extraction region [8]. The trend towards lower emittances for higher charge states can be clearly seen.

One possible interpretation for this dependence is that higher charge state ions are confined closer to the axis and are extracted from a smaller (virtual) extraction hole. These results are consistent with the model that highly charged ions are created closer to the center of the ECR plasma, where hot electrons are confined. The low charge state ions on the other hand can be produced at the outer shell of the ECR plasma and therefore can have higher emittance values [7].

In addition, it is experimentally observed, that the emittance values for ions with the same magnetic rigidity but different masses decreases for heavier masses. Figure 6 shows an emittance measurement performed on the AECR-U ion source at LBNL for various charge states of oxygen, bismuth, krypton, and single charged ions of hydrogen and helium [7]. For the same mass to charge ratio, heavier ions have lower emittances than lighter ions. Similar results were found in the VENUS source (see figure 6) and other sources [4,9].

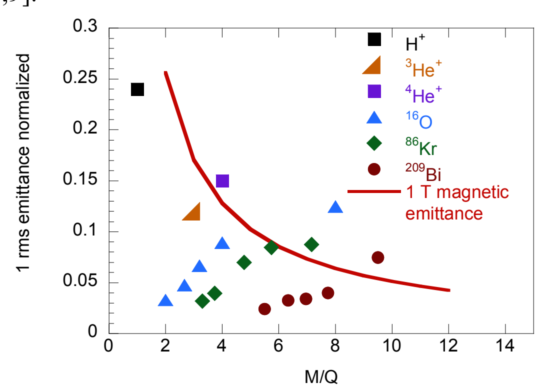

Figure 6: Emittance measurements on the AECR-U for various masses in comparison with predicted emittances for an extraction magnetic field of 1 T.

Another important contribution to emittances measured from ECR ion sources is the plasma stability. The ion beam emittance can easily change a factor of 2 or 3 at comparable ion beam intensities for unstable plasma conditions. Therefore, the emittance should always be determined for a range of plasma conditions to quantify the possible range of emittance values (see figure 7).

One of the causes of this wide spread in emittance values can be the plasma chamber wall condition, which strongly influences the plasma confinement and stability. If the ECR source had been opened to ambient atmosphere or the ion beam had been changed from one metal to another, it can take 2 to 3 days before the lowest emittance and peak performance values can be achieved. Consequently, during rapid beam changes involving high intensity metal ion beams, the source and beam transport tunes have to be balanced between maximum intensity and beam quality. The emittance measurement is then used as an online ion source tuning aid.

DEPENDENCE OF THE MEASURED EMITTANCE ON THE AXIAL MAGNETIC EXTRACTION FIELD

Since 2000 the LBNL ECR ion source VENUS has been developed as a prototype injector source for the FRIB facility. Therefore, extensive ion beam emittance studies have been performed to characterize the ion source. Since the VENUS ECR ion source is fully superconducting the confinement field can be adjusted and optimized for different ECR heating frequencies and the influence of the magnetic field on the emittance can be studied with the same beam line and experimental set-up. In case of the VENUS ECR ion source the source is equipped with an 18 GHz as well as a 28 GHz microwave system. The extraction fields used when operated using 18 GHz are tuned to field strengths between 1.2 and 1.6 T and for 28 GHz field between 2 and 2.4 T. Figure 7 shows a summary of a series of emittance measurements for xenon ion beams produced using 18 GHz and 28 GHz confinement fields and heating. It can be clearly seen that the emittance values for 28 GHz operation are in general higher than for 18 GHz operation. Within the data set a wide spread of the emittance data can be seen, which is due to the varying plasma conditions.

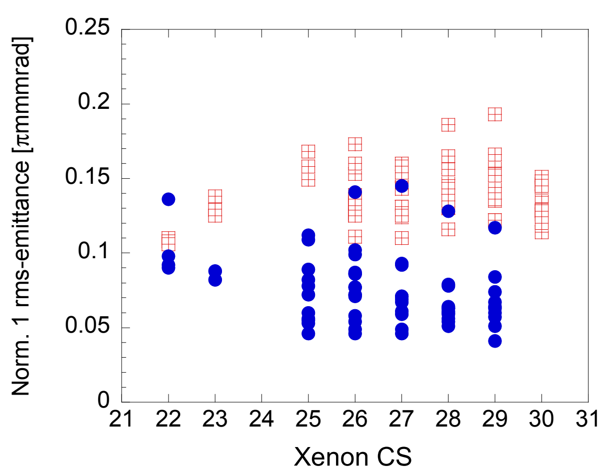

Figure 7: Measured emittance of medium charge state xenon ion beams extracted from VENUS for 18 and 28 GHz operation.

Figure 8 and 9 show measured ion beam emittances for light and heavy ion beams extracted from the VENUS ECR ion source. As expected, 18 GHz emittances (figure 8) are smaller than 28 GHz emittances (figure 9). The values scale roughly linear with the change in magnetic field, but in both cases the emittance values are below the predicted emittances (solid lines) for a beam that would fill the full plasma extraction electrode. This observation also supports the argument of a smaller 'virtual' extraction hole.

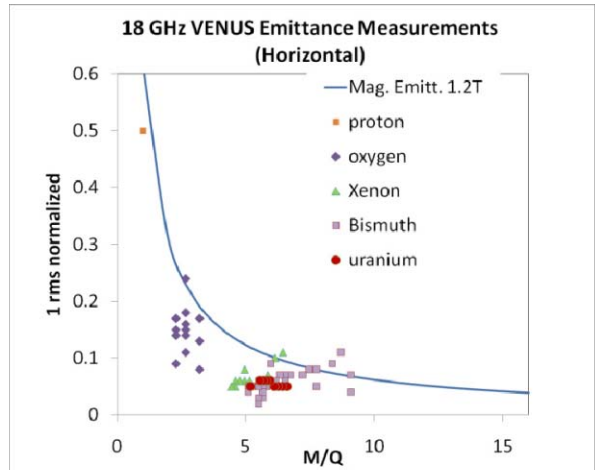

Figure 8: Measured ion beam emittances for ion beams extracted from the VENUS ECR ion source using 18 GHz plasma heating and confinement fields.

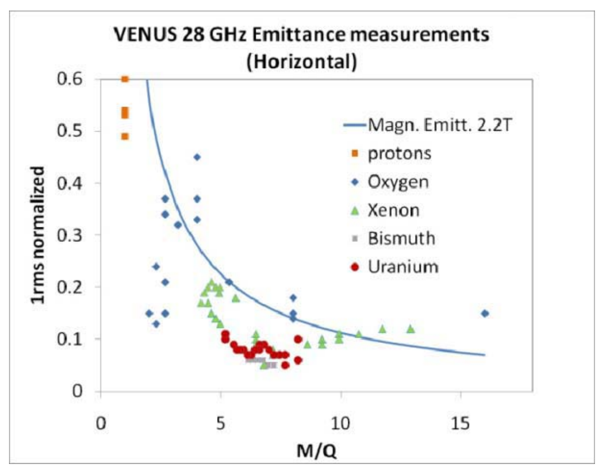

Figure 9: Measured ion beam emittances for ion beams extracted from the VENUS ECR ion source using 18 GHz plasma heating and confinement fields.

INFLUENCE OF THE ION BEAM INTENSITY ON THE EMITTANCE

The influence of the ion beam intensity on the emittance was also investigated. The measurements show that the emittance values of a single charge state remain nearly constant over a wide range of intensities as long as the total extracted ion beam current (the sum over all species present in the extracted beam) remains similar.

In figure 10 data for low to high ion beam intensities for Bi^{31+} and Bi^{29+} are shown together with total transported ion beam from the ion source. The emittance varies ±10% over this intensity range if the total extracted beam is nearly constant. Contrary, the emittance seems to grow linearly with the intensity if the total extracted ion beam intensity increases (figure 11). One possible explanation could be space charge effects in the extraction region.

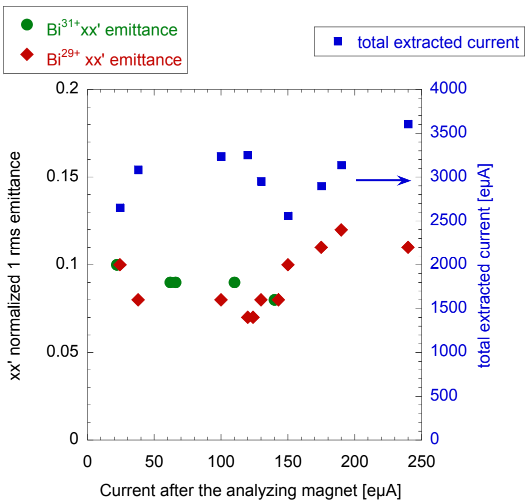

Figure 10: Emittance measurements for low and high intensity beams of Bi^{29+} and Bi^{31+}. The total extracted and transported beam is also plotted.

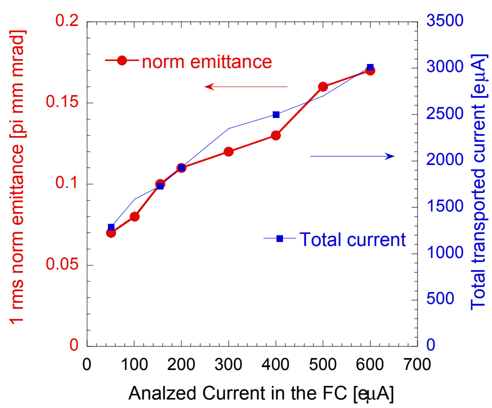

Figure 11: O^{6+} ion beam emittance in dependence of the extracted ion beam intensity. On the left axis the beam emittance is plotted, on the right axis the total ion beam current is plotted.

DEFINING AND MEASURING INITIAL CONDITIONS OF THE IONS BEAMS AT THE EXTARCTION APERATURE

One of the simplifications of equation 2 is the assumption that the ion density across the plasma outlet aperture is homogenous. However, measurements using optical ion beam diagnostics and beam emittance scanners have clearly shown that this assumption is incorrect. As an example, figure 12 shows a picture of a multispecies beam extracted from the AECR-U containing argon and oxygen ions about 1.5 m downstream of the extraction hole close to the object point of the mass analyzing magnet. A solenoid lens upstream was optimized to focus Ar^{11+}. The other charge states are either over-focused or under-focused by the magnetic lens and some can be seen as rings around the core of the beam. The complex structure of the beam can be easily seen.

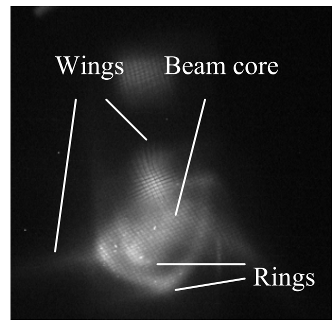

Figure 12: Picture of a non mass analyzed beam on a quartz plate containing charge state distributions of argon and oxygen. Different charge states and ions are visible as rings in the picture, since the solenoid lens is optimized to focus only one of the charge states.

OPTICAL BEAM DIAGNOSTICS USED FOR THE LOW ENERGY BEAM LINES

As the kinetic energy of the ions in low energy beam lines are small, only a few materials are suitable as scintillators. Three scintillator crystals, KBr, quartz, and BaF_2 have been tested at LBNL and compared with each other. In addition, CsI(TI) crystals are successfully used in ANL as scintillator for a pepperpot emittance scanner [5]. Typically to avoid charging of the insulator surfaces, highly transparent meshes are placed before the scintillator material. Of the scintillator materials tested at LBNL, KBr has the highest light yield (about 4 times higher than quartz and BaF_2, see figure 13) [4].

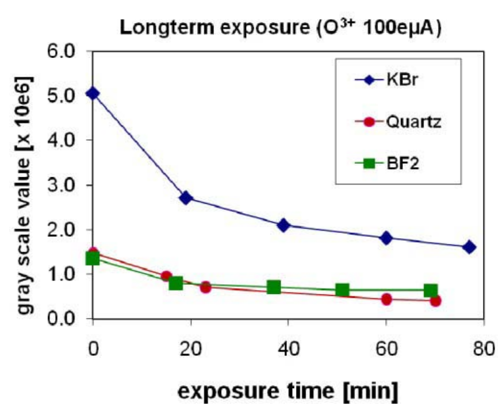

Figure 11: Longterm exposure of KBr, Quartz, and BF_2 with 100eμA of O^{3+}

All of the scintillators showed about the same degradation in light yield for prolonged exposure to high intensity beams (figure 11). Because of this degradation of light yield the exposure time to the beam should be minimized and the crystal cleaned from time to time or exchanged. This is in particular critical for optical pepperpot emittance scanners to avoid measurement errors due to the light yield changes in the most intensive regions of the beam.

For the high intensity beams quartz crystals are used as they are inexpensive and can be easily changed. For the optical pepperpot KBr crystals are used to maximize the light yield and sensitivity of the diagnostic [10].

MODELING OF THE INITIAL ION BEAM DISTRIBUTION AT THE EXTRACTION APERTURE

In order to correctly simulate the ion beam transport, the initial conditions at the plasma extraction aperture must be known. Since there is currently no generally accepted model of how to derive the correct initial conditions, assumptions must be made [12]. Optical diagnostics are important tools to validate and develop these models.

LBNL has developed a semi-empirical model to describe the ion beam distribution at the extraction aperture. In this model, ion sputter marks found inside the plasma chamber are used as initial distribution of the ions inside the plasma chamber and tracked to the extraction aperture [11]. While this model is overly simple and cannot describe the complex processes in the plasma, it results in several observed features such as the triangular structure of the beam and the reduced spatial distribution at the extraction aperture (see figure 14) [12].

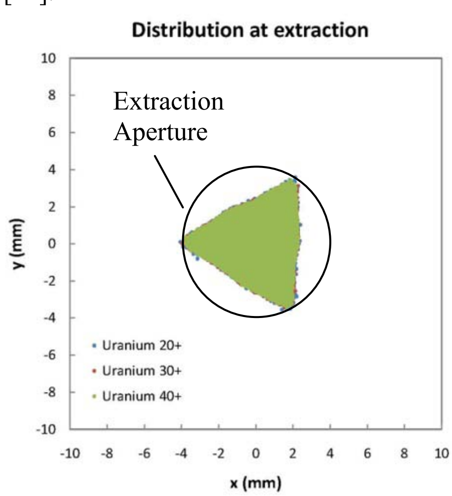

Figure 14: Spatial distributions for uranium ions at the extraction aperture [12]

In addition, the beam models can also experimentally reproduce observed hollow structures of some ion beam species due to space charge forces in focal points of the beam line. Figure 15 shows a comparison of a simulated multispecies ion beam profile (oxygen and carbon CSD) and its image on the quartz scintillator plate. Qualitatively the agreement is good.

However, one of the limitations of the model is that it assumes the same initial spatial distribution of the ions at the bias disk for all charge states and therefore cannot describe the emittance reduction for the highest charge states as observed in the experiments (see figures 5 and 6) nor can it describe the emittance reduction for heavy masses for beams that have the same rigidity. Further refinements will be needed in an iterative process between experiment and simulations to derive to initial conditions with charge state and mass dependent ion beam distributions.

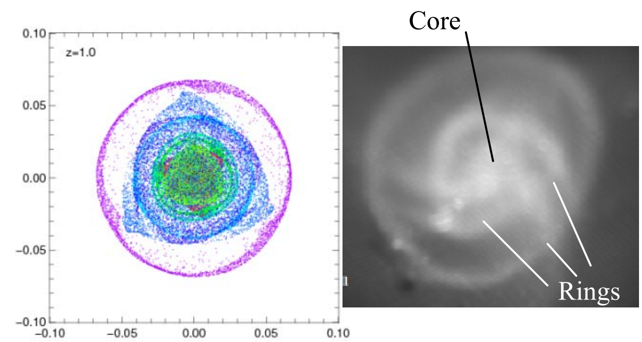

Figure 15: Comparison of a simulated multispecies beam containing oxygen and carbon ions and the image of the beam on a quartz scintillator. The beam line solenoid lens has been optimized on O^{7+} and so the lower charge states are underfocused (rings on the outer parts of the image) [13].

NEUTRALIZATION LEVEL OF THE BEAM

Ionization of background gas by the passing ion beam produces both low energy electrons and ions inside of the beam envelope. These electrons can be confined by the beam and effectively reduce the beam's positive space-charge potential, while the newly created positive background gas ions are ejected from the beam center. Since ECR ion source injectors are mostly used in CW mode, it has been generally assumed that ECR ion beams in magnetic transport systems are fully neutralized. However, on VENUS it was experimentally observed that the ion beam transmission decreased with increasing ion beam current, which would be consistent with space charge effects in the beam. To measure the level of neutralization an electrostatic energy analyzer was constructed at LBNL that measures the energy of background gas ions expelled by the space charge potential of the ion beam.

It could be demonstrated that at low beam line pressures (10^{-8} mbar) used for high charge state ion beam injectors, the neutralization times are too long to fully neutralize the ion beam. At this low pressure, the loss rate of confined electrons seems to exceed the rate of their trapping. Only when the pressure was raised to the low 10^{-6} mbar, close to fully neutralized beams could be observed [13]. This is consistent with measurements at the cyclotron institute in Jyvaskyla where it was observed that the ion beam emittance values decreased with increasing pressure in the beam line [9]. However, increasing the pressure in the beam line also increases the charge exchange rate of highly charged ions, and is therefore not an option for high charge state ion injectors. Simulations show that using a 70 to 80% neutralization level agrees well with experimental emittance and beam profile measurements [12], but further measurements will be necessary to determine the degree of neutralization along the beam line and in various beam line components (in particular inside the analyzing magnet).

SUMMARY

Properties of the ion beams extracted from ECR ion source plasmas and transported through a low energy beam transport line are complex. Multispecies ion beams with triangular density distributions are extracted from a high magnetic field region that adds a rotational component to the beam, which leads to transverse emittance growth in dependence of the magnetic rigidity. In addition, the confinement of the ions in the plasma and the plasma stability influence the emittance values. Ideally the ion beam distribution inside the center of the ECR ion source plasma should be measured. But since this is challenging there is a need for highly spatial-resolved ion beam diagnostics that can provide 2D beam profile and 4D emittance measurements along the beam line to iteratively develop a consistent model for the initial ion distribution at the extraction aperture. In addition, in order to further refine the simulation models diagnostics should be developed to determine the degree of beam neutralization along the beam transport line.

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